NASA TM X-53175

# VACUUM SYSTEM SIMULATION AND

# MULTIPORT SYSTEM FEASIBILITY STUDY

by C. T. EGGER AND J. B. GAYLE
Propulsion and Vehicle Engineering Laboratory

NASA

*George C. Marshall*

*Space Flight Center,*

*Huntsville, Alabama*

TECHNICAL MEMORANDUM X-53175


VACUUM SYSTEM SIMULATION AND
MULTIPORT SYSTEM FEASIBILITY STUDY


By

C. T. Egger
and
J. B. Gayle

George C. Marshall Space Flight Center

Huntsville, Alabama

ABSTRACT

*/5892*

The pumpdown, degassing, and ultimate vacuum characteristics of single and multiport vacuum systems under various operating conditions are compared by means of a mathematical model and electrical analog computer simulation.

Using this technique, it was shown that a large multiport vacuum system employing a large diffusion pump is feasible and affords a number of advantages not attainable in an array of individual single-chamber systems of nominally similar capabilities.

Experimental data for an existing single-chamber laboratory system are in close agreement with performance characteristics predicted by the simulation method.

NASA - GEORCE C. MARSHALL SPACE FLIGHT CENTER

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER

---

TECHNICAL MEMORANDUM X-53175

---

VACUUM SYSTEM SIMULATION AND
MULTIPORT SYSTEM FEASIBILITY STUDY

By

C. T. Egger
and
J. B. Gayle

MATERIALS DIVISION
PROPULSION AND VEHICLE ENGINEERING LABORATORY

## ACKNOWLEDGMENT

# TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

## LIST OF TABLES

# LIST OF SYMBOLS

A    Surface area of bell jar and baseplate from which desorption is occurring

L    Leak rate

M    Molecular weight

n    (Subscript) relates to bell jar(s) being evacuated

o    (Subscript) refers to initial conditions (t = 0)

P    Pressure

S    Molecular conductance ($S_4$ = pump speed and conductance)

t    Time

V    Volume

$\psi$    Defined by Equation 2

$\phi$    Function of $P_4$ defined in Figure 3

## VACUUM SYSTEM SIMULATION AND
## MULTIPORT SYSTEM FEASIBILITY STUDY

## SUMMARY

The pumpdown, degassing, and ultimate vacuum characteristics of single and multiport vacuum systems under various operating conditions are compared by means of a mathematical model and electrical analog computer simulation.

Using this technique, it was shown that a large multiport vacuum system employing a large diffusion pump is feasible and affords a number of advantages not attainable in an array of individual single-chamber systems of nominally similar capabilities.

Bell jar pressure interactions were shown to be minimal; however, the effect of retarded return to ultimate vacuum must be evaluated for each application considered. All assumptions are conservative estimates, however, so a somewhat more rapid response at a lower pressure level may be expected.

Experimental data for an existing laboratory system agree with performance characteristics predicted by the simulation method and lend credence to the modeling and simulation technique.

## INTRODUCTION

During recent years, the Materials Division has been engaged in the preliminary evaluation of materials for space and high vacuum use. Several vacuum systems used for weight loss studies have undergone constant evolution as improved components and techniques were developed. The point has been reached, however, where the procurement of new systems must be evaluated against major modifications of those now in use. This report describes a feasibility study of one of the possible new systems.

Of the major experimental problems now confronted, quick attainment of programmed temperature and rapid evacuation to a low ultimate pressure are two of greatest concern. The quick attainment of programmed temperature is practically independent of the vacuum system itself; however, one possible method for attaining the other objective

is through use of a multiport system such as that described herein. At the same time, it would be advantageous to add bell jars at a minimum expenditure of funds and laboratory space while reducing expected maintenance. Further, a contingency capability for extreme pumping speed at better than $10^{-7}$ torr is desirable.

During many months of investigation and planning, components and packaged systems offered by all known reputable vacuum suppliers have been studied. In the final analysis, considerations such as performance, cost, maintenance, and space conservation indicated that a centralized, multiport vacuum system affords a number of advantages that are not attainable in an equivalent array of individual systems.

## DEFINITION OF PROBLEM

Figure 1 shows the major components and characteristics of the apparatus, which consists basically of a large diffusion pump and six or eight bell jars. For purposes of the study, only three bell jars were considered.

The central diffusion pump, backed by a small diffusion booster and a mechanical forepump of intermediate size, would have a high nominal pumping speed and an ultimate vacuum of approximately $10^{-9}$ torr with a cryogenic baffle.

An enlarged upper chamber would provide sufficient spacing between bell jars to make room for individual pneumatic valves for automatic sequencing and control. The bell jars would each contain a minimum volume consistent with the space required for weight loss studies and could be partially evacuated before being exposed to the diffusion pump (FIG 2).

Trapping would be tandem, with liquid nitrogen baffles below each bell jar to supplement the large baffle above the diffusion pump. The conductances of all components were considered; however, the cryopumping capabilities of the liquid nitrogen-cooled surfaces were neglected. In this respect, the results obtained are conservative.

Above each baffle is a pneumatic valve which will permit isolation and venting of the bell jar without disturbing the diffusion pump or exposing the cold baffle to atmospheric conditions. The proposed arrangement provides for automatic monitoring to rough-pump the bell jar (FIG 2) and then switch to pumping via the diffusion pump. This control did not enter into the analysis.

Major factors of interest were pumping speed at the bell jars, magnitude and duration of pressure interactions among bell jars (due to cycling or consecutive rather than concurrent shutdown/pumpdown), and the effects of gas load due to leakage, outgassing, and specimen volatilization. The most important factor prompting this study was the concern regarding the pressure interactions ("bursts") among bell jars expressed by representatives from three leading vacuum equipment suppliers. A further incentive was the desire to develop a flexible program for vacuum system simulation which would be available for general laboratory use in system design and analysis.

## CONDITIONS AND ASSUMPTIONS

A roughing level of approximately $10^{-2}$ torr is expected for the enlarged chamber (250 liters) above the diffusion pump before operation of this pump. Similarly, each of the 15-liter bell jars would be evacuated to $10^{-2}$ torr or less prior to automatic exposure to the high vacuum port (FIG 2). The brief times required for valves to open have been neglected in the analysis.

Component pumping speeds and conductances for the cases cited are given in Table I. Pressure gradients within open chambers, specifically the bell jars and the enlarged chamber, were assumed to be negligible. The assumed diffusion pump speed characteristics for cases 4-12, a typical manufacturer's curve, are shown in FIG 3. Curves for cases 13 and 14 are not shown but had a similar source.

Leakage, outgassing, and volatilization rates are outlined in Table I. The maximum leak rate cited is conservative in that leak detection methods which are available permit reduction of the rate below that assumed. However, the outgassing rate is a somewhat nebulous factor and becomes relatively more serious as the pressure falls lower and lower. Cases 4-6[*] represent sequential pumpdown of three bell jars for a minimal-leakage system, and case 7 simulates simultaneous pumpdown under similar conditions. Cases 8-10 start with a zero-leakage station, add a minimal-leakage station, and conclude with the pumpdown of a bell jar containing an evaporating material. In this way, practically all ranges of experimental conditions are included in the simulation. Cases 11 and 12 indicate the effectiveness of the high capacity pumping system when it is used to evacuate relatively large environmental chambers.

---

[*] All case numbers numerically equal the corresponding figure numbers for the convenience of the reader.

3

## MATHEMATICAL MODEL

Mathematical representation of the simulated systems consists of writing differential material balances around each bell jar and around the diffusion pump with its overhead chamber. Each balance equates the change of pressure (by means of the PV product) to the net input-output flows as determined by pumping, outgassing, leakage, and volatilization.

For each bell jar $\underline{n}$:

$$V_n \frac{dP_n}{dt} = L_n - S_n (P_n - P_4) + A_n \psi_n (t, A_n, S_n, M) \qquad (1)$$

where the $\psi_n$ term represents desorption of the atmospheric contaminants from the bell jar and base plate. The computer program was arranged so that the $\psi_n$ term applies for bell jar $\underline{n}$ only when that bell jar is being pumped down from rough vacuum ($P_{o,n} = 10^{-2}$ torr).

Data for obtaining constants for the $\psi_n$ equation were taken from Dayton[*] and were normalized as A/S conditions which led to:

$$\psi n(t, A_n, S_n, M) = \frac{1.03 \times 10^{-11}}{1 + 676 \left(\frac{A_n}{S_n \sqrt{M}}\right)} \epsilon^{\left[-\frac{t}{2.7 \times 10^5 (11.1 (A_n/S_n))}\right]} + 1.8 \times 10^{-6} \epsilon^{-0.04 \sqrt{t}} \qquad (2)$$

Behavior of the diffusion pump and overhead chamber is given by:

$$V_4 \frac{dP_4}{dt} = L_4 + \sum_n S_n (P_n - P_4) - S_4, \text{ Max. } P_4 \phi \qquad (3)$$

where $\phi$ is a function of $P_4$ as shown in FIG 3.

For later cases where only a single bell jar was employed, $\underline{n}$ is equated to 1, and the subscript 4 is retained for the diffusion pump area.

Consideration of the equipment and inspection of EQU 1-3 indicate that three major phases of pumpdown would be expected for a single, desorbing bell jar. The first phase, controlled by the $\Delta P$ terms, is rapid and accounts for the bulk of the gas. Phase two embodies a gradual pressure decline as the adsorbed materials are slowly released and pumped away. Attainment of a constant pressure level governed by

---

[*]B. B. Dayton, "1959 Sixth National Symposium on Vacuum Technology, Transactions," Pergamon Press, London, 1960, p. 101. A molecular weight of 50 was assumed for all calculations.

4

the leak rates and pump limitations is represented by the third phase.
The pressure behavior at any time is the sum total of these phases, so
gradual transitions rather than sharp changes of mode are expected.

As shown by instability problems with the analog computer and
difficulties in numerical integration of the equations on a digital
computer, arithmetic problems can be expected because of the use of
small differences of relatively large numbers during late (low
pressure) stages of the pumpdown. Simulation was attempted on both
types of computers, but only the results from the analog (Electronic
Associates Model 131-R) are shown here. The solutions are slightly
inaccurate because of the need for frequent interruptions for rescaling.
The great time span and the pressure variations over approximately
seven orders of magnitude made analog simulation unusually difficult.

A modified Runge-Kutta numerical integration was used for initial
pumpdown simulation using the Burroughs 5000 digital computer, but,
after approximately 15 seconds, a simple Euler integration was found
to be more satisfactory. In no case, however, was it possible to
maintain stability once the rate of pressure change began to level off;
therefore, the digital approach was abandoned.

## RESULTS

Figures 4-6 show analog results for cases 4-6 from Table I.
This series is for sequential pumpdown of three bell jars and behaves
as expected. The bell jar being pumped reacts practically the same
in each case, and the other bell jar pressures follow closely that
above the diffusion pump. High-pressure "bursts" are short-lived
and reach only about $10^{-4}$ torr, but it may be significant that
repumping to pressures below $10^{-7}$ is slow because of the load on the
diffusion pump from the bell jar being pumped down the first time
(with outgassing). Pressures below $10^{-6}$ torr, however, are recovered
almost instantaneously.

The similarity of the bell jar pressure curves in FIG 4 (one bell
jar) and FIG 7 (three bell jars) shows that the diffusion pump system
is capable of handling multiple chambers simultaneously. Thus, the
results shown in FIG 4-7 demonstrate that such a system is feasible.
Further performance characteristics are discussed in the following
paragraphs.

External leaks at the specified rates are noticeable only near or
at the ultimate pressure, as seen by comparing FIG 4 and 8, the latter
having zero bell jar leakage. Until about 30,000 seconds ($10^{-8}$ torr),
the curves are identical.

5

As would be expected for practically identical circumstances, bell jar pressure curves for FIG 5 and 9 coincide throughout the pumpdown.

Even the high evaporation rate simulated by case 10 (Table I) does not have a large influence on the pumpdown rate, as shown by comparison of FIG 6 and 10. Only after about 10,000 seconds ($10^{-7}$ torr) do the curves begin to diverge. Of course, a poorer ultimate vacuum would be expected for case 10, but analog computer instabilities precluded further definition of the curves.

As mentioned above, the pressure bursts feeding back into low-pressure bell jars from $10^{-2}$ torr chambers being exposed to the system are very brief and do not appreciably exceed $10^{-4}$ torr. The electro-balance disturbance (during weight loss studies) at such pressures would be negligible, and, for peak evaporation loads, the slow return to ultimate pressures probably would not impose more than half a decade pressure sacrifice. A further factor is that the model again is conservative in that a uniform pressure was assumed in the chamber above the diffusion pump. In reality, most of the molecules leaving the degassing bell jar would be directed towards the cryobaffle and, because of mean free path at the low pressures involved (about $5 \times 10^{-7}$), would not be deflected back into other bell jars. Cryopumping of the evaporated molecules on both small and large liquid nitrogen-cooled baffles would add still another safety factor.

In keeping with the desire for a contingency capability for high pump speeds at low pressures mentioned in the introduction, cases 11 and 12 (Table I) for large chambers atop the diffusion pump were simulated. Figures 11 and 12 show that such a capability exists but that surface degassing times may be prohibitive. In such cases, thermal bakeout of the walls to expedite removal of adsorbed materials would warrant serious consideration. Reference to the source for EQU 2 would show which terms are temperature dependent. Assumed room temperatures would have to be replaced by bakeout temperature in the equation to adapt the model to bakeout simulation.

The concept of a single port system having a high vacuum pumping station matched in size with the bell jar valve and cryobaffle is examined in FIG 12, where points shown are crossplotted from FIG 4 for comparison. As expected from the higher diffusion pumping capacity of the multiport pump, the latter case exhibits more rapid pumpdown, which is another factor in favor of the multiport system.

Because all the foregoing was applied to hypothetical systems, an experimental check on the accuracy of the simulation was desirable if not imperative. Therefore, an existing laboratory system (designated 4A) was simulated by measuring components, calculating parameters, and

using the manufacturer's curve for the diffusion pump behavior (case 14, Table I). Both calculated bell jar and calculated diffusion pump pressures are shown in FIG 14, where the plotted points are from actual system tests which were requested and received by the authors from a third party having no knowledge of the simulated results. Considering the many assumptions involved in the model, particularly in the degassing relationship (EQU 2), the agreement between system performance and simulated results is believed to be very satisfactory.

Insofar as computation methods could be compared, it may be stated that in every case where digital computer results were obtained (usually for the first 20 seconds of pumpdown) agreement with analog results was within the accuracy of the graphs.

## CONCLUSIONS

The mathematical model and electrical analog simulation technique provides a reasonable representation of high vacuum equipment.

Using this technique, it was shown that a multiport vacuum system employing a large diffusion pump is feasible if not preferable to individual single-chamber systems of supposedly similar capacities.

Bell jar pressure interactions were shown to be minimal; however, the effect of retarded return to ultimate vacuum must be evaluated for each application considered. Experience with high vacuum weight loss studies indicates that such a phenomenon probably is not critical, particularly when the pressure gradient between the test oven and the bell jar chamber is considered.

It should be noted that the advantages of the multiport concept are due largely to high pumping speed plus high bell jar port conductance. Use of multiple chambers set on sidearm tubes would greatly reduce the conductances (Table I) and drastically diminish the utility and attractiveness of the multiport type of system. Thus, the direct overhead chamber-to-bell jar chamber connection is of utmost importance.

Preliminary cost studies indicated that a six-port 32-inch diffusion pump having 10-inch (15 liter) bell jars over nominal 6-inch ports (arranged as in FIG 1 and 2) would be competitive in price with six separate nominal 6-inch systems while offering many extra features. Complete layout and cost studies for both types of systems should precede a final choice.

The entire simulation scheme involves conservative assumptions and estimates which, if precisely known, would undoubtedly result in hypothetical performance curves even more favorable to the multiport system concept.

TABLE I

INPUT DATA FOR SIMULATED CASES

| CASE AND FIGURE NO. | BELL JARS INVOLVED | INITIAL PRESSURE, [1] TORR | | | | VOLUME, LITERS | | | | CONDUCTANCE, [2] LITERS/SEC | | | | DESORBING AREA, [3] CM$^2$ | | | LEAK RATE, TORR - LITERS/SEC | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $P_{10}$ | $P_{20}$ | $P_{30}$ | $P_{40}$ | $V_1$ | $V_2$ | $V_3$ | $V_4$ | $S_1$ | $S_2$ | $S_3$ | $S_4$ | $A_1$ | $A_2$ | $A_3$ | $L_1$ | $L_2$ | $L_3$ | $L_4$ |
| 4 | 1 | $10^{-2}$ | - | - | $10^{-9}$ | 15 | - | - | 250 | 888 | - | - | $2.84 \times 10^4$ | 3550 | - | - | $7.6 \times 10^{-7}$ | - | - | $7.6 \times 10^{-7}$ |
| 5 | 1,2 | CONT | $10^{-2}$ | - | CONT | 15 | 15 | - | 250 | 888 | 888 | - | $2.84 \times 10^4$ | - | 3550 | - | $7.6 \times 10^{-7}$ | $7.6 \times 10^{-7}$ | - | $7.6 \times 10^{-7}$ |
| 6 | 1,2,3 | CONT | CONT | $10^{-2}$ | CONT | 15 | 15 | 15 | 250 | 888 | 888 | 888 | $2.84 \times 10^4$ | - | - | 3550 | $7.6 \times 10^{-7}$ | $7.6 \times 10^{-7}$ | $7.6 \times 10^{-7}$ | $7.6 \times 10^{-7}$ |
| 7 | 1,2,3 | $10^{-2}$ | $10^{-2}$ | $10^{-2}$ | $10^{-9}$ | 15 | 15 | 15 | 250 | 888 | 888 | 888 | $2.84 \times 10^4$ | 3550 | 3550 | 3550 | $7.6 \times 10^{-7}$ | $7.6 \times 10^{-7}$ | $7.6 \times 10^{-7}$ | $7.6 \times 10^{-7}$ |
| 8 | 1 | $10^{-2}$ | - | - | $10^{-9}$ | 15 | - | - | 250 | 888 | - | - | $2.84 \times 10^4$ | 3550 | - | - | 0.0 | - | - | $7.6 \times 10^{-7}$ |
| 9 | 1,2 | CONT | $10^{-2}$ | - | CONT | 15 | 15 | - | 250 | 888 | 888 | - | $2.84 \times 10^4$ | - | 3550 | - | 0.0 | $7.6 \times 10^{-7}$ | - | $7.6 \times 10^{-7}$ |
| 10[4] | 1,2,3 | CONT | CONT | $10^{-2}$ | CONT | 15 | 15 | 15 | 250 | 888 | 888 | 888 | $2.84 \times 10^4$ | - | - | 3550 | 0.0 | $7.6 \times 10^{-7}$ | $2.24 \times 10^{-5}$ | $7.6 \times 10^{-7}$ |
| 11 | 6' CUBE | $10^{-2}$ | - | - | $10^{-9}$ | 6,116 | - | - | 50 | $7.07 \times 10^4$ | - | - | $2.84 \times 10^4$ | $5.1 \times 10^5$ | - | - | $7.6 \times 10^{-7}$ | - | - | $7.6 \times 10^{-7}$ |
| 12 | 10' CUBE | $10^{-2}$ | - | - | $10^{-9}$ | 28,320 | - | - | 50 | $7.07 \times 10^4$ | - | - | $2.84 \times 10^4$ | $1.41 \times 10^6$ | - | - | $7.6 \times 10^{-6}$ | - | - | $7.6 \times 10^{-7}$ |
| 13 | 1 | $10^{-2}$ | - | - | $10^{-9}$ | 15 | - | - | 2.5 | 888 | - | - | 2885 | 3550 | - | - | $7.6 \times 10^{-7}$ | - | - | $7.6 \times 10^{-7}$ |
| 14[5] | 1 | $10^{-2}$ | - | - | $10^{-6}$ | 15 | - | - | 1.0 | 20 | - | - | 212 | 3550 | - | - | $7.6 \times 10^{-7}$ | - | - | $7.6 \times 10^{-7}$ |

NOTES:

(1) "CONT" indicates starting at pressure existing at end of previous case.
(2) $S_4$ is a pump speed, the maximum rate given for the diffusion pump employed.
(3) Desorption occurs only for bell jar(s) being evacuated from $10^{-2}$ torr.
(4) Includes volatilization of sample for $L_3$ of case 10.
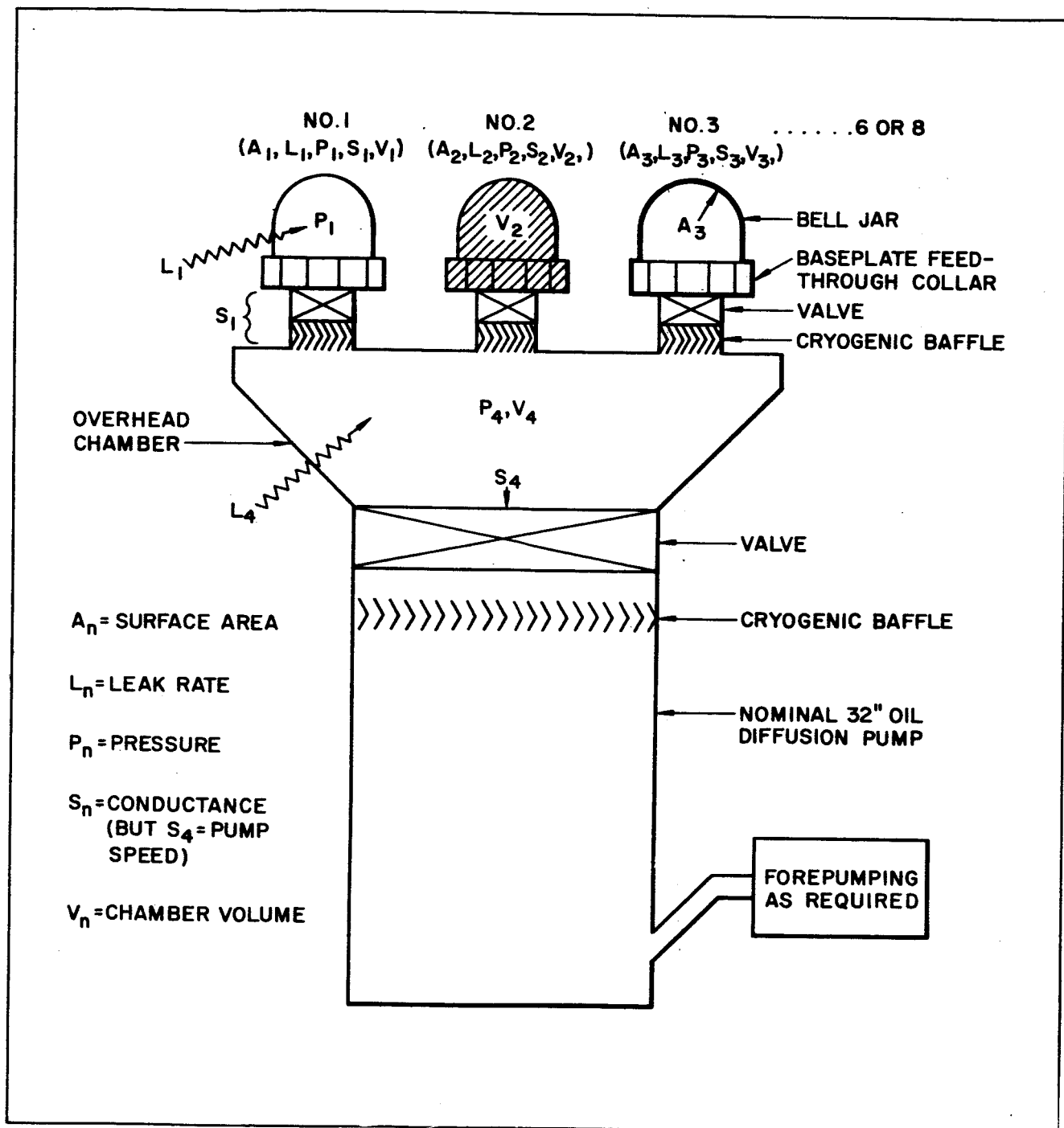(5) Similar to MSFC "4A" vacuum system.

NO.1
$(A_1, L_1, P_1, S_1, V_1)$

NO.2
$(A_2, L_2, P_2, S_2, V_2,)$

NO.3 ......6 OR 8
$(A_3, L_3, P_3, S_3, V_3,)$

$P_1$

$L_1$

$V_2$

$A_3$

$S_1$

BELL JAR

BASEPLATE FEED-
THROUGH COLLAR

VALVE

CRYOGENIC BAFFLE

OVERHEAD
CHAMBER

$P_4, V_4$

$S_4$

$L_4$

VALVE

$A_n$= SURFACE AREA

CRYOGENIC BAFFLE

$L_n$= LEAK RATE

$P_n$= PRESSURE

NOMINAL 32" OIL
DIFFUSION PUMP

$S_n$= CONDUCTANCE
(BUT $S_4$= PUMP
SPEED)

$V_n$= CHAMBER VOLUME

FOREPUMPING
AS REQUIRED

FIGURE 1. MULTIPORT SYSTEM; HIGH VACUUM SCHEMATIC
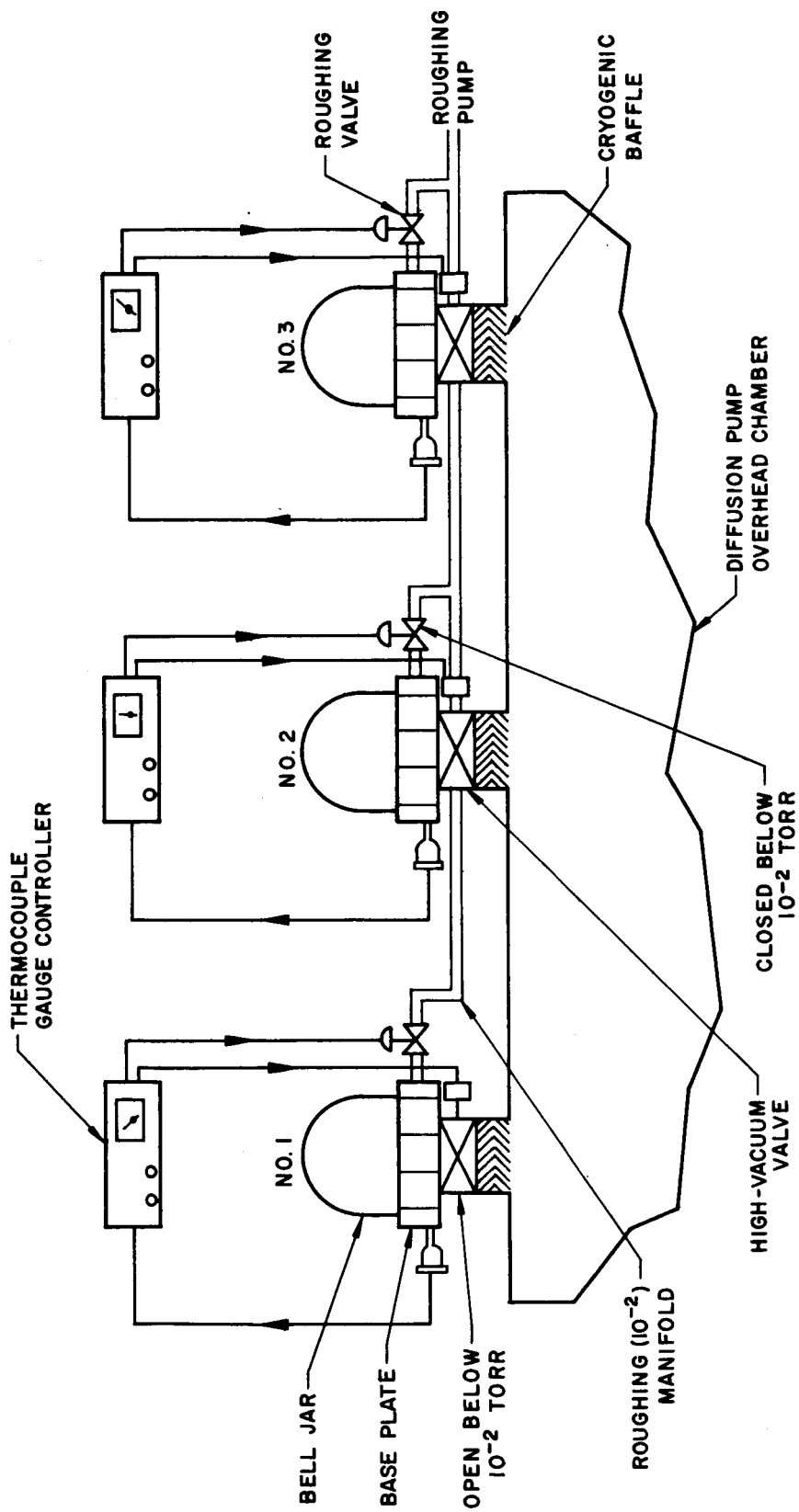
FIGURE 2. CONTROL SYSTEM FOR AUTOMATIC ROUGHING AND SWITCHING TO DIFFUSION PUMPING
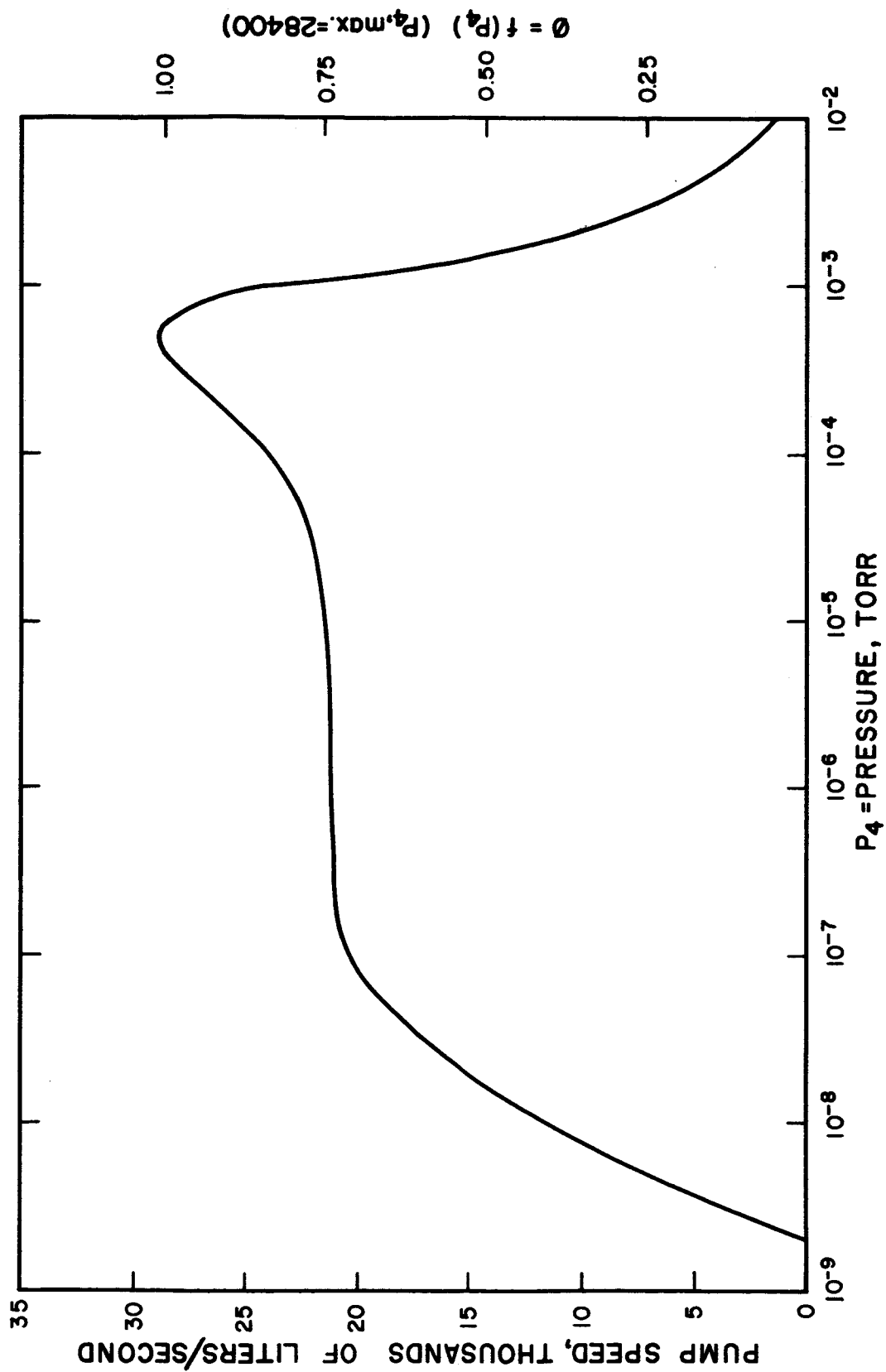
FIGURE 3. DIFFUSION PUMP PERFORMANCE CURVE

11
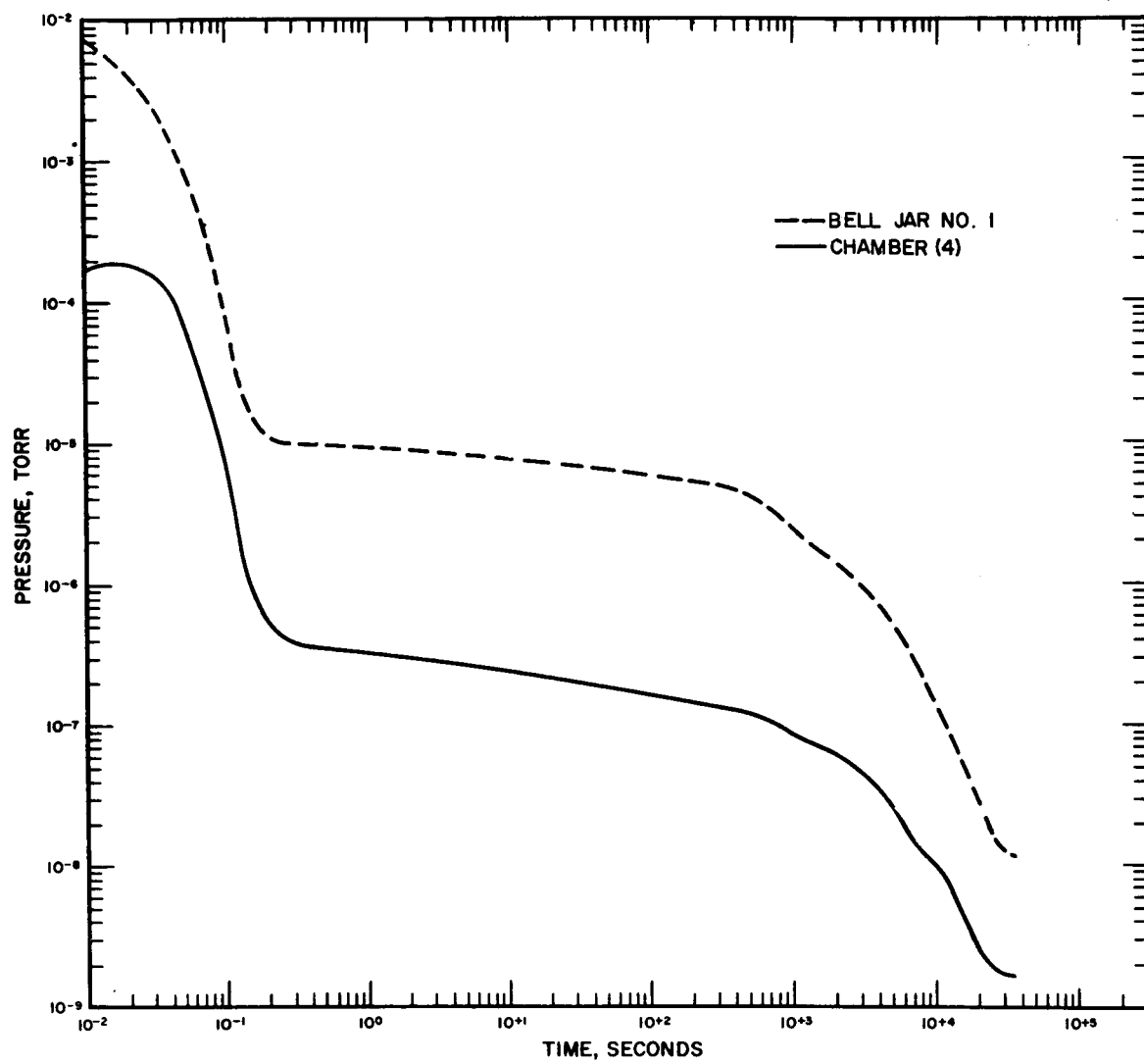
FIGURE 4. SIMULATION RESULTS FOR CASE 4

12
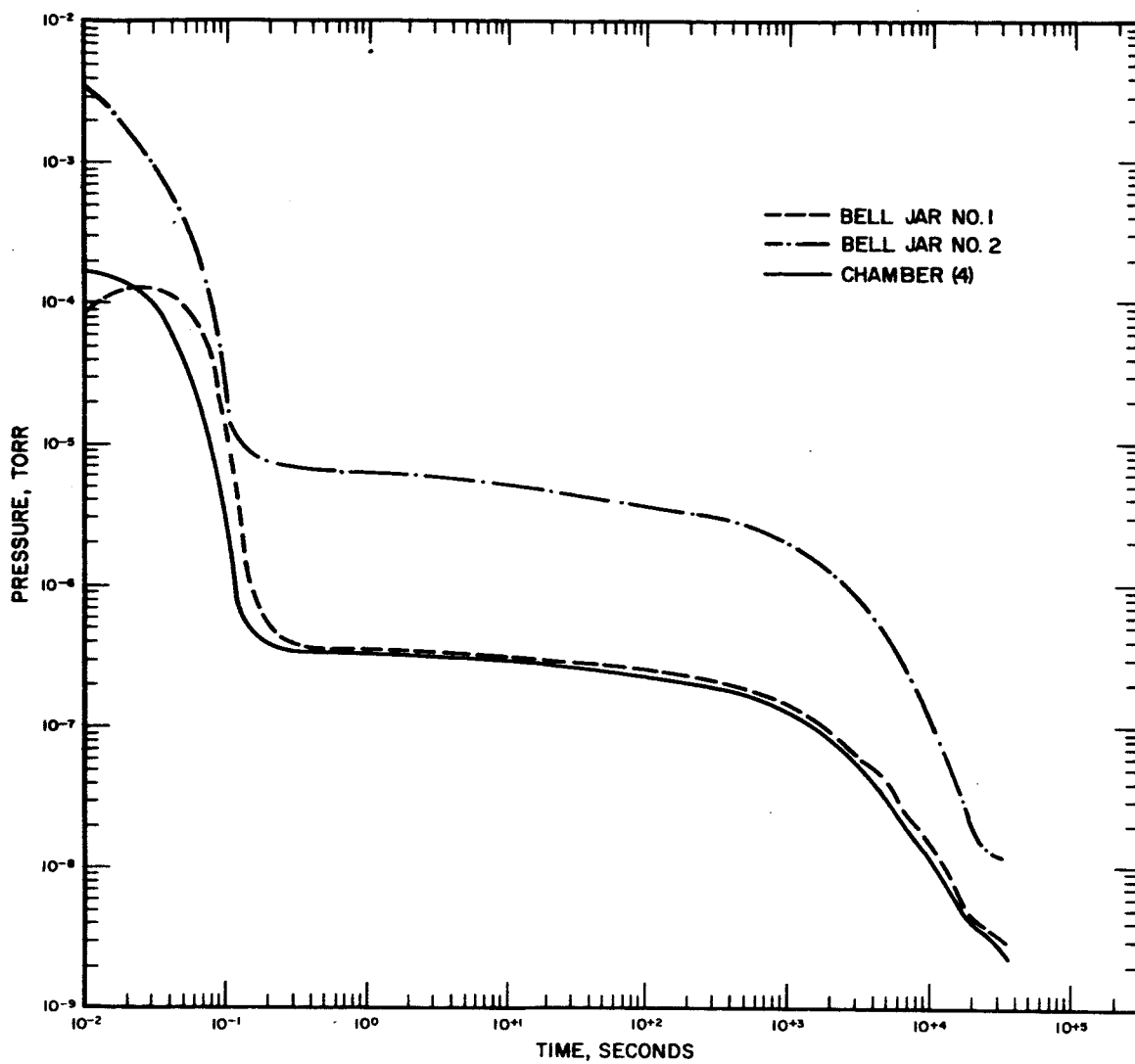
FIGURE 5.   SIMULATION RESULTS FOR CASE 5
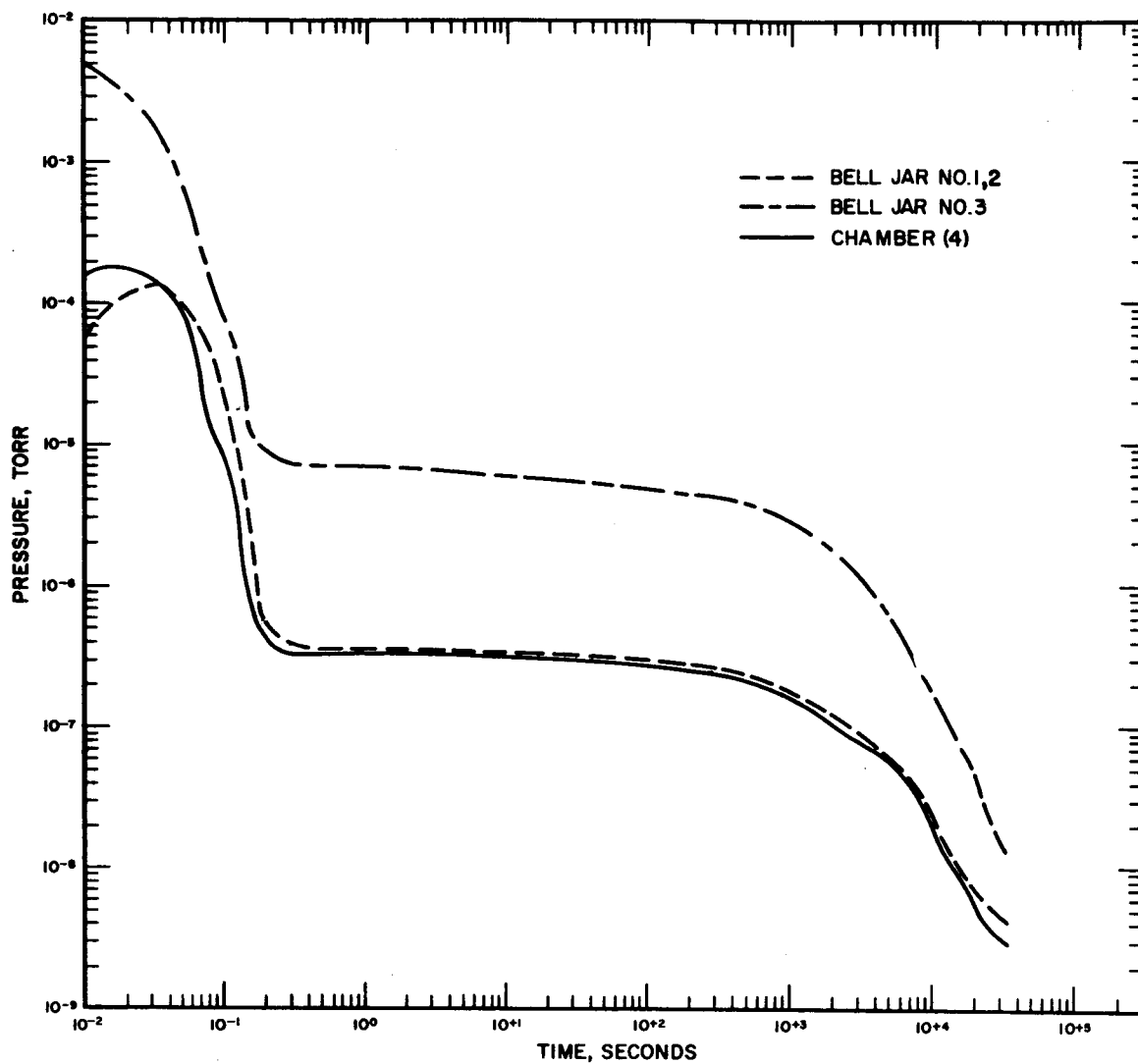
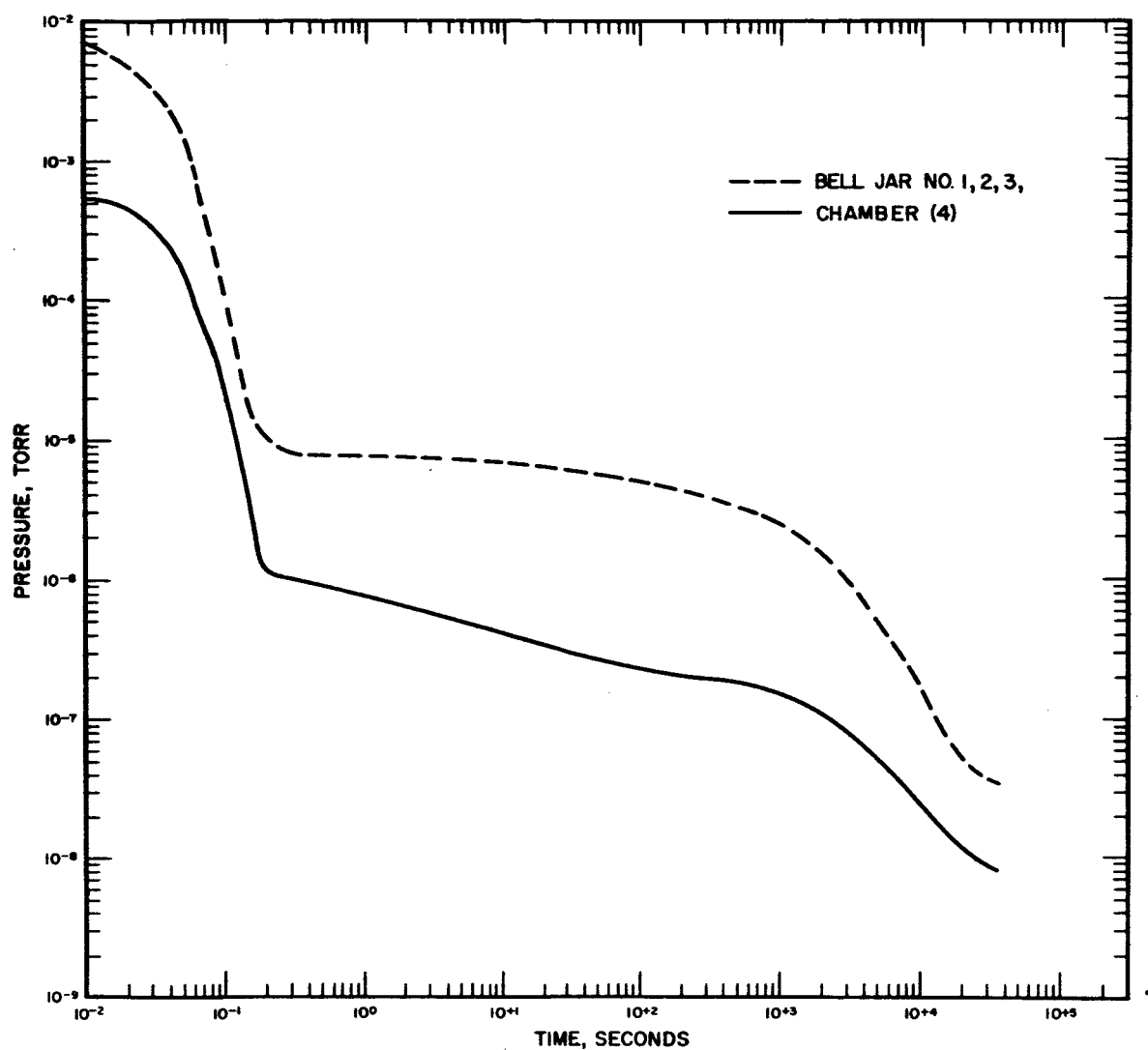FIGURE 6.   SIMULATION RESULTS FOR CASE 6
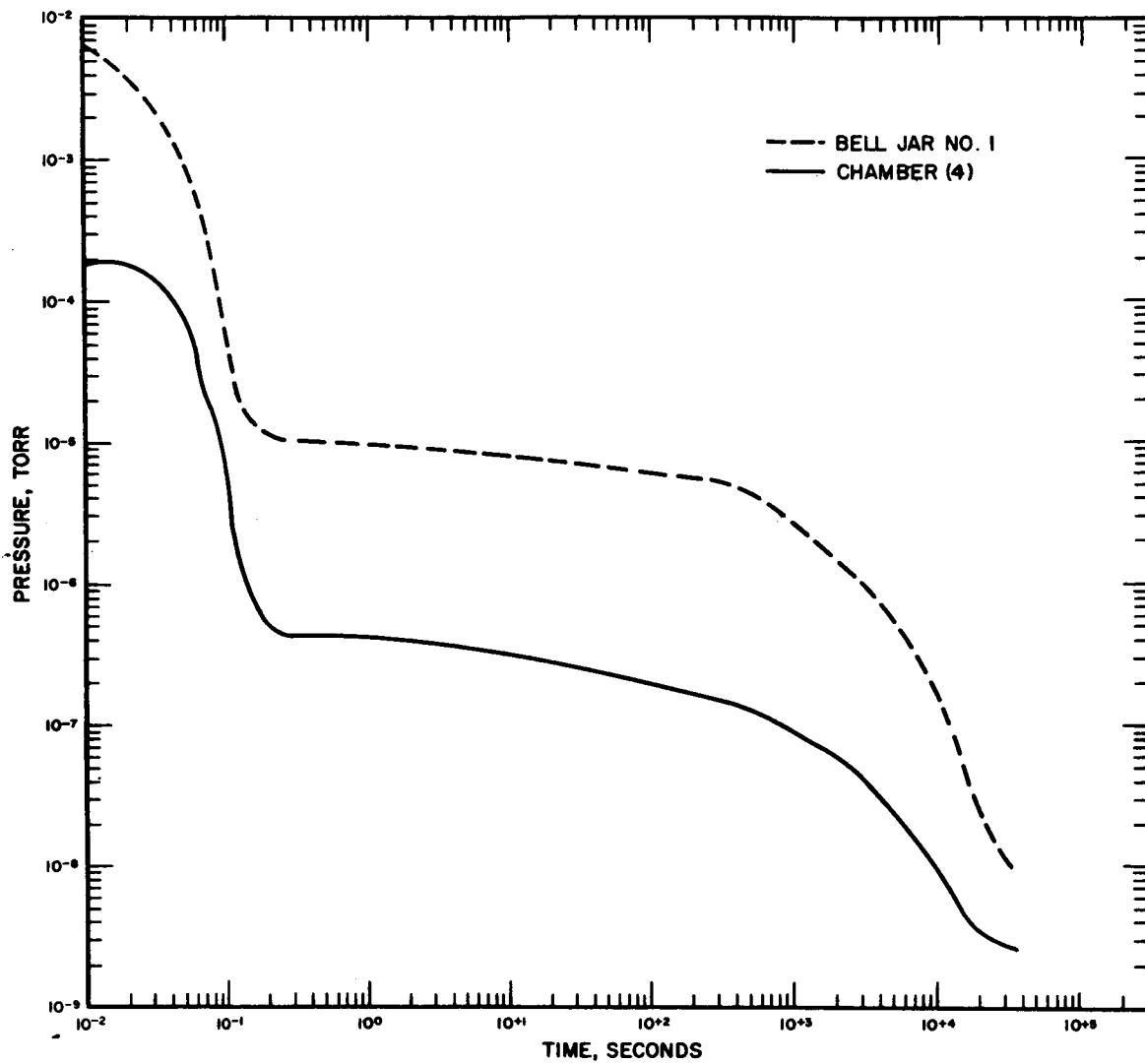
FIGURE 7. SIMULATION RESULTS FOR CASE 7

15

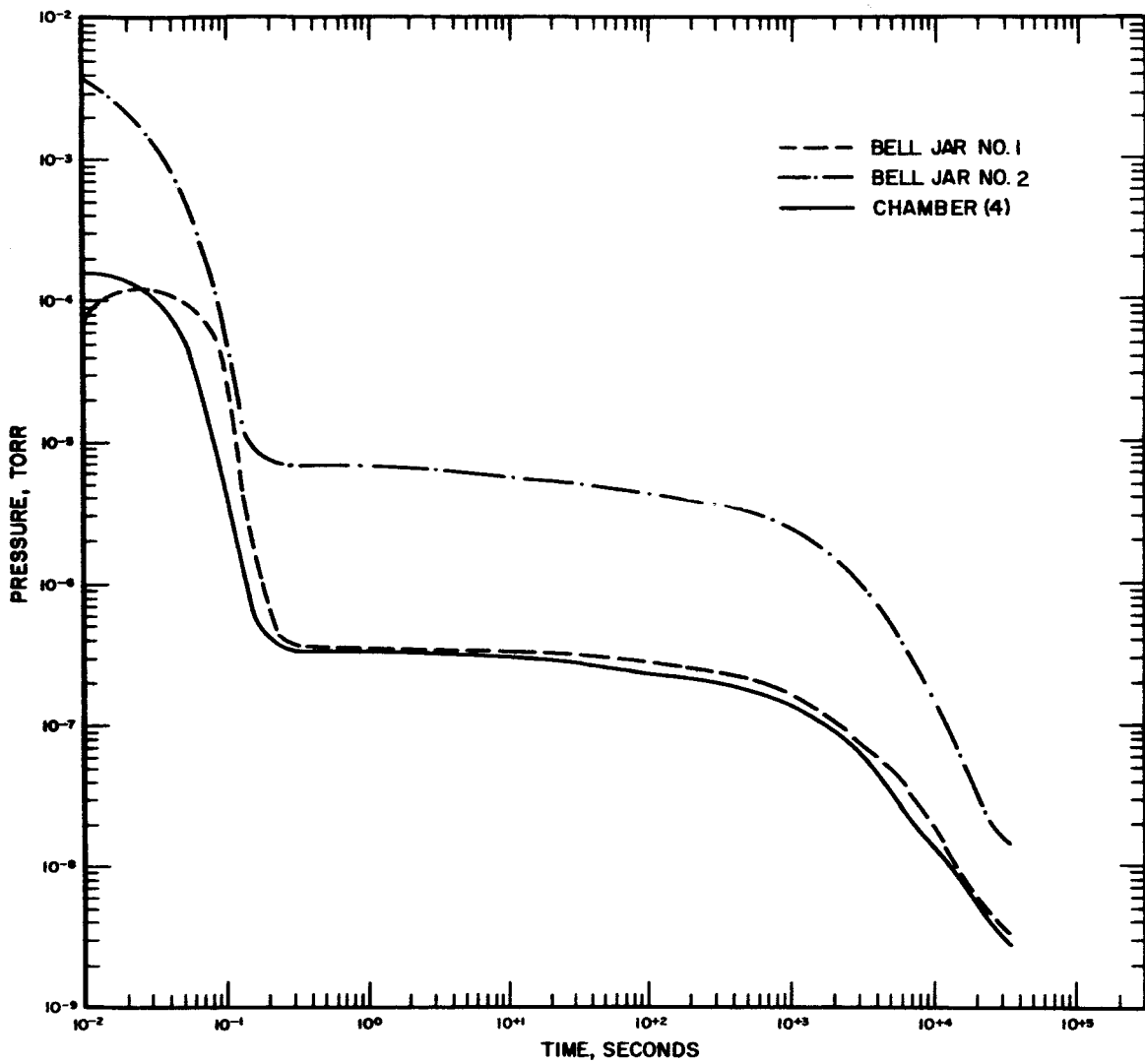FIGURE 8.   SIMULATION RESULTS FOR CASE 8
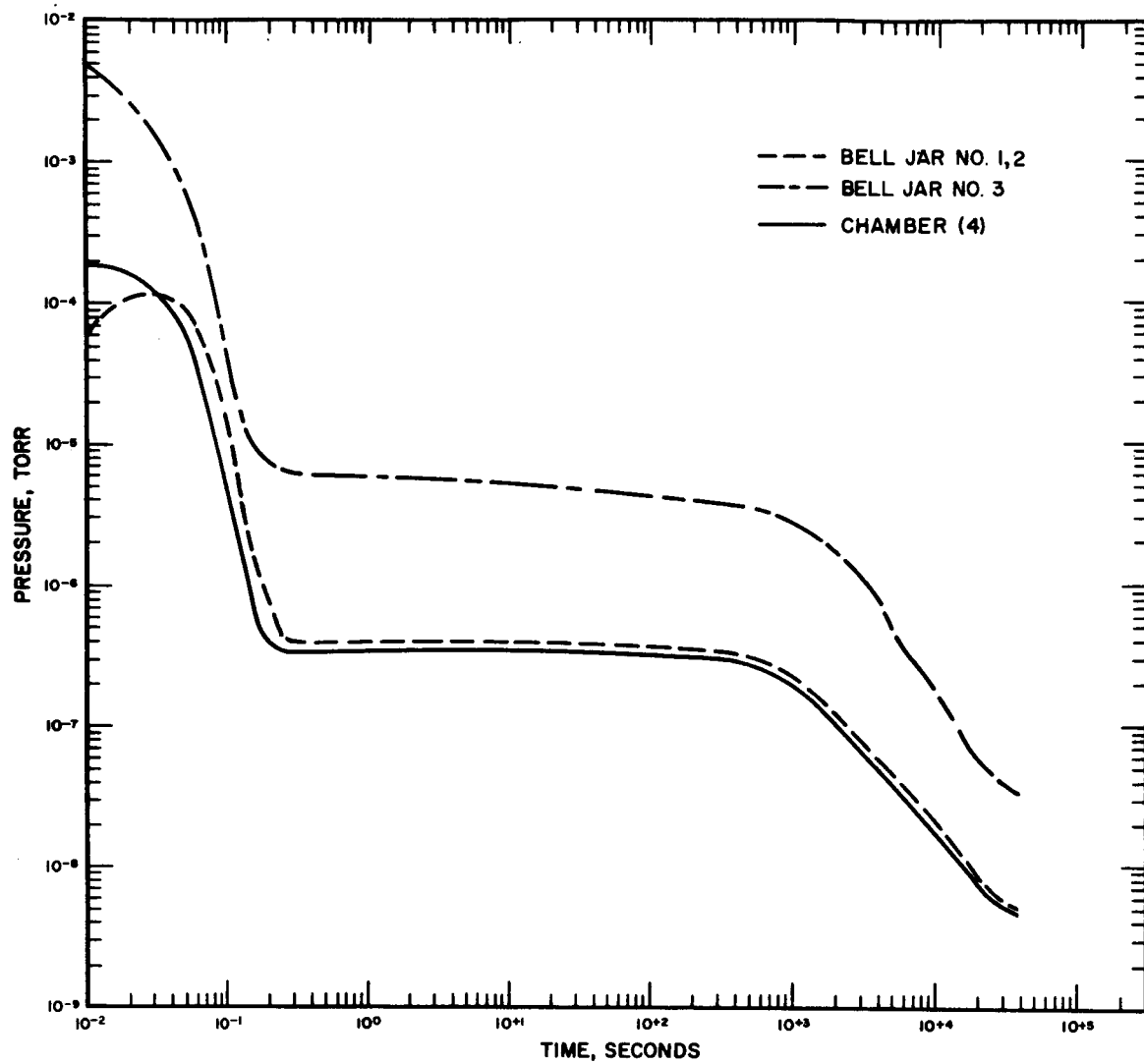
FIGURE 9.   SIMULATION RESULTS FOR CASE 9

FIGURE 10. SIMULATION RESULTS FOR CASE 10
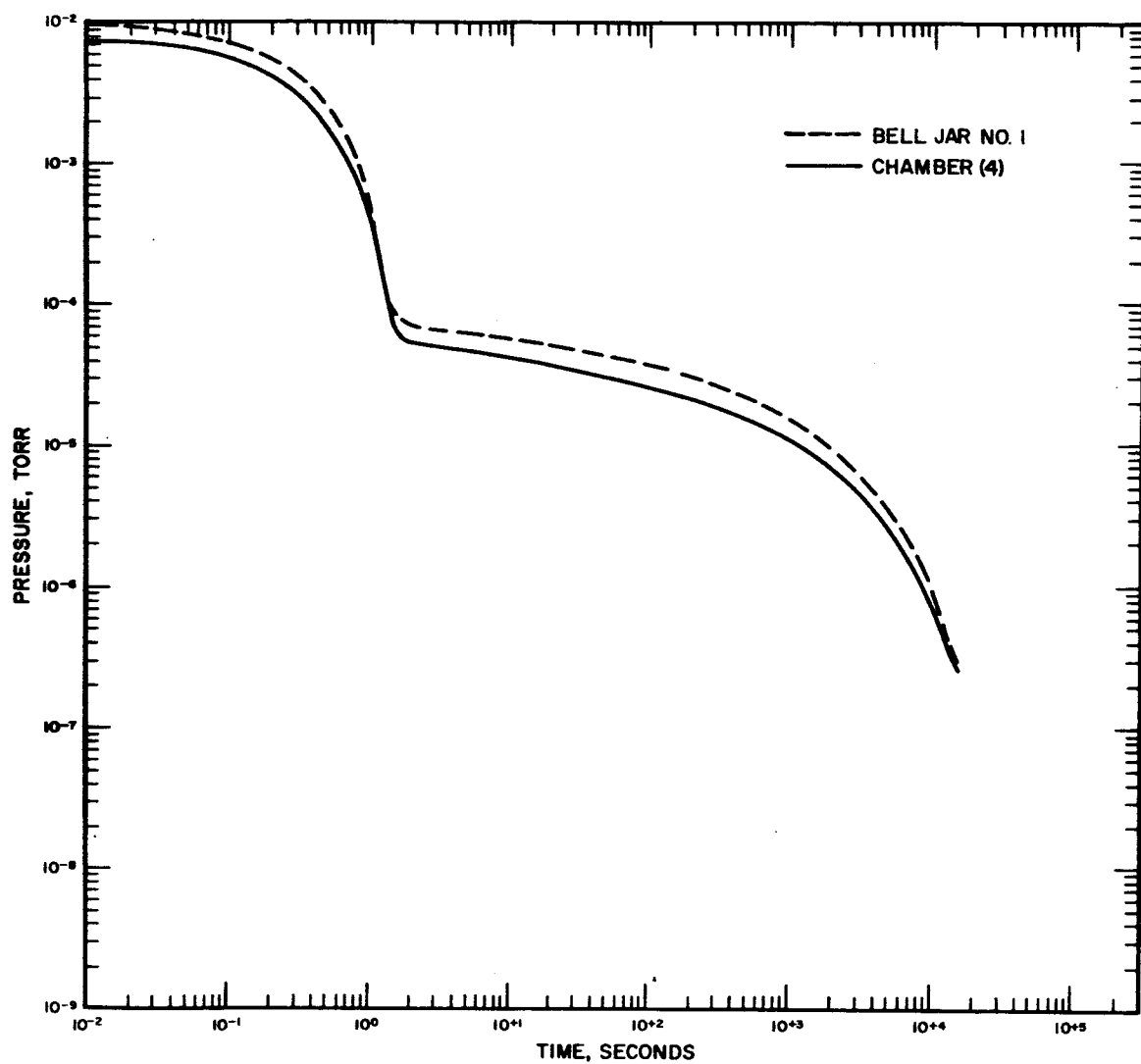
18

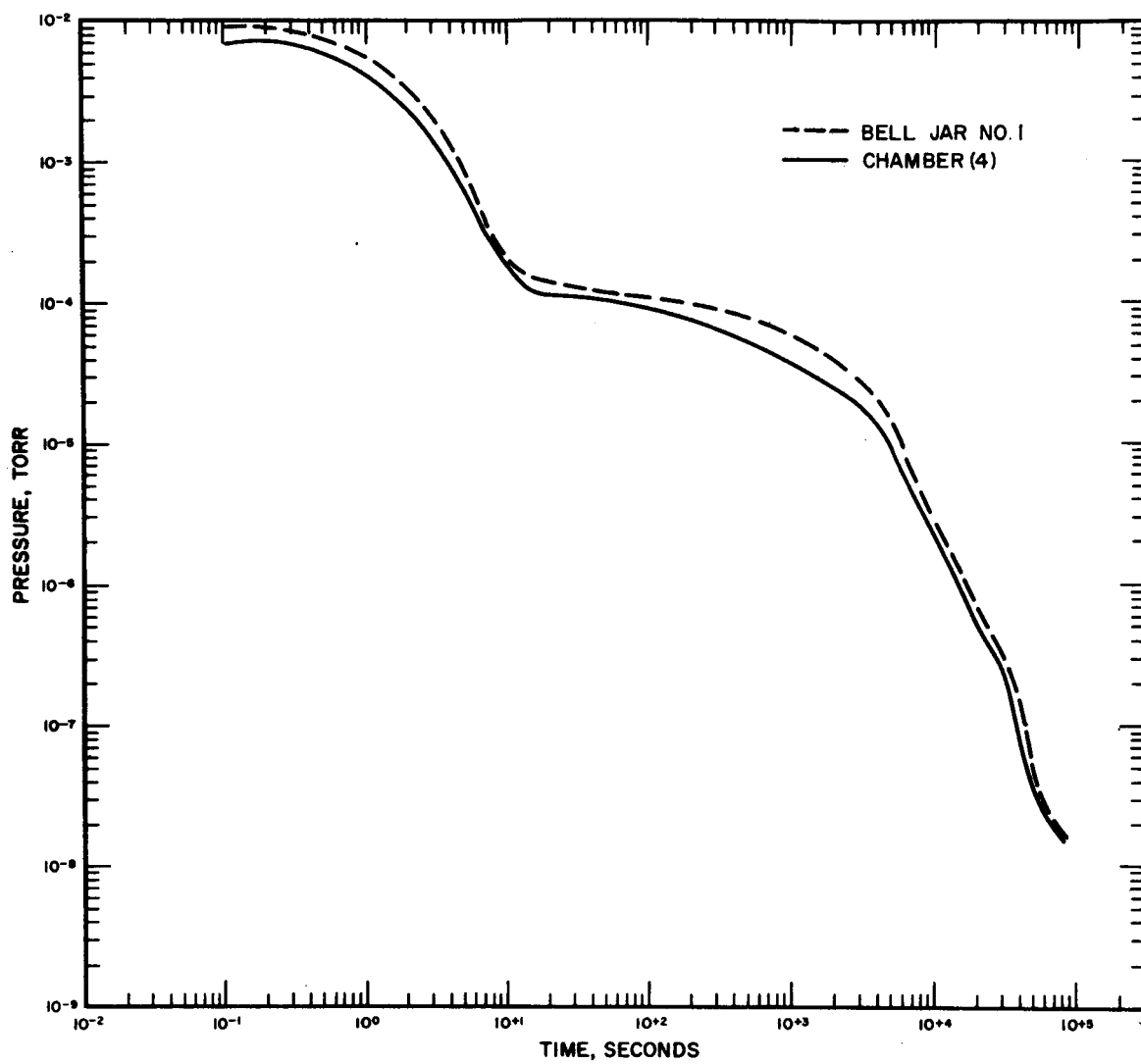FIGURE 11.   SIMULATION RESULTS FOR CASE 11

FIGURE 12. SIMULATION RESULTS FOR CASE 12
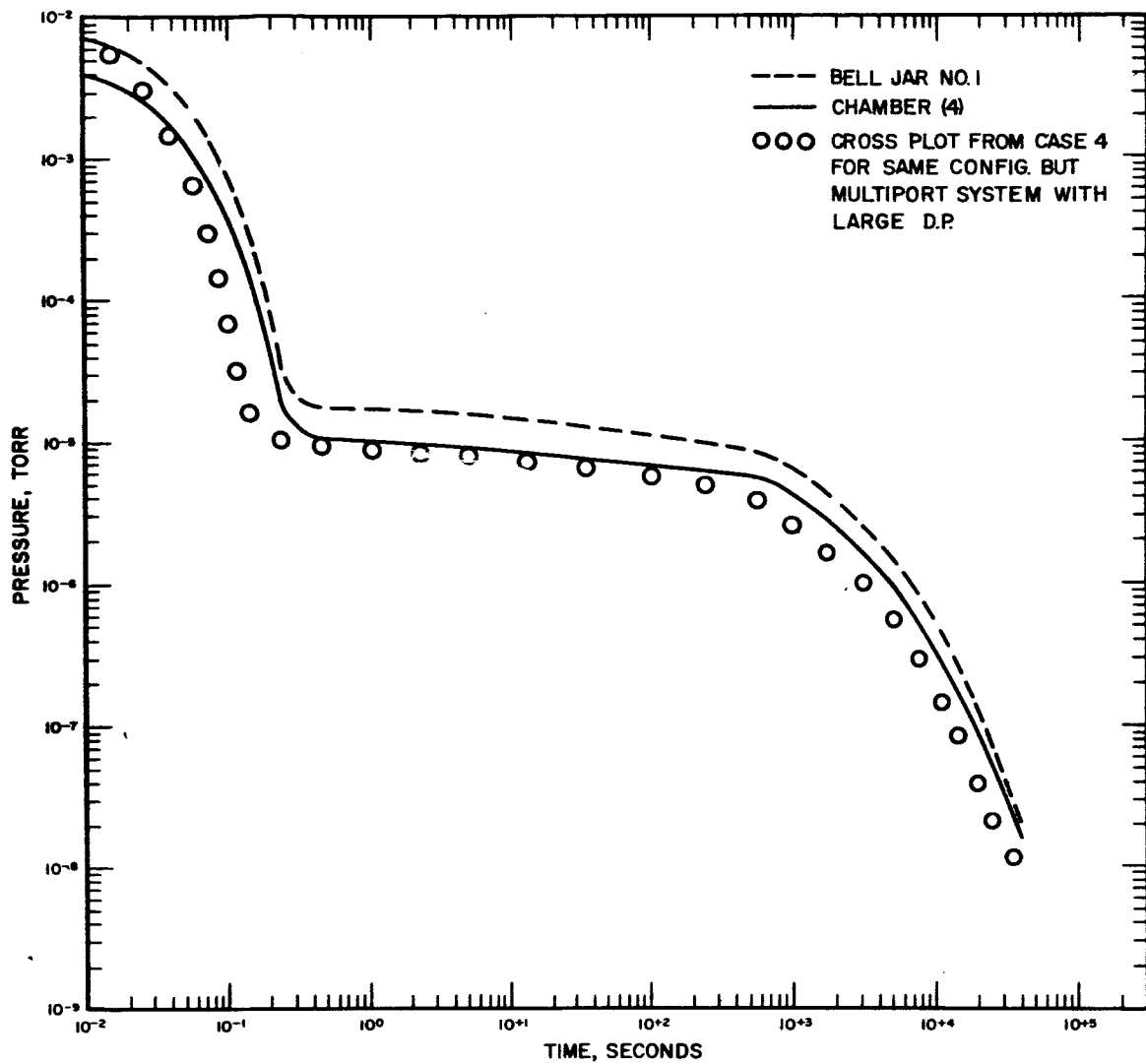
FIGURE 13.  SIMULATION RESULTS FOR CASE 13
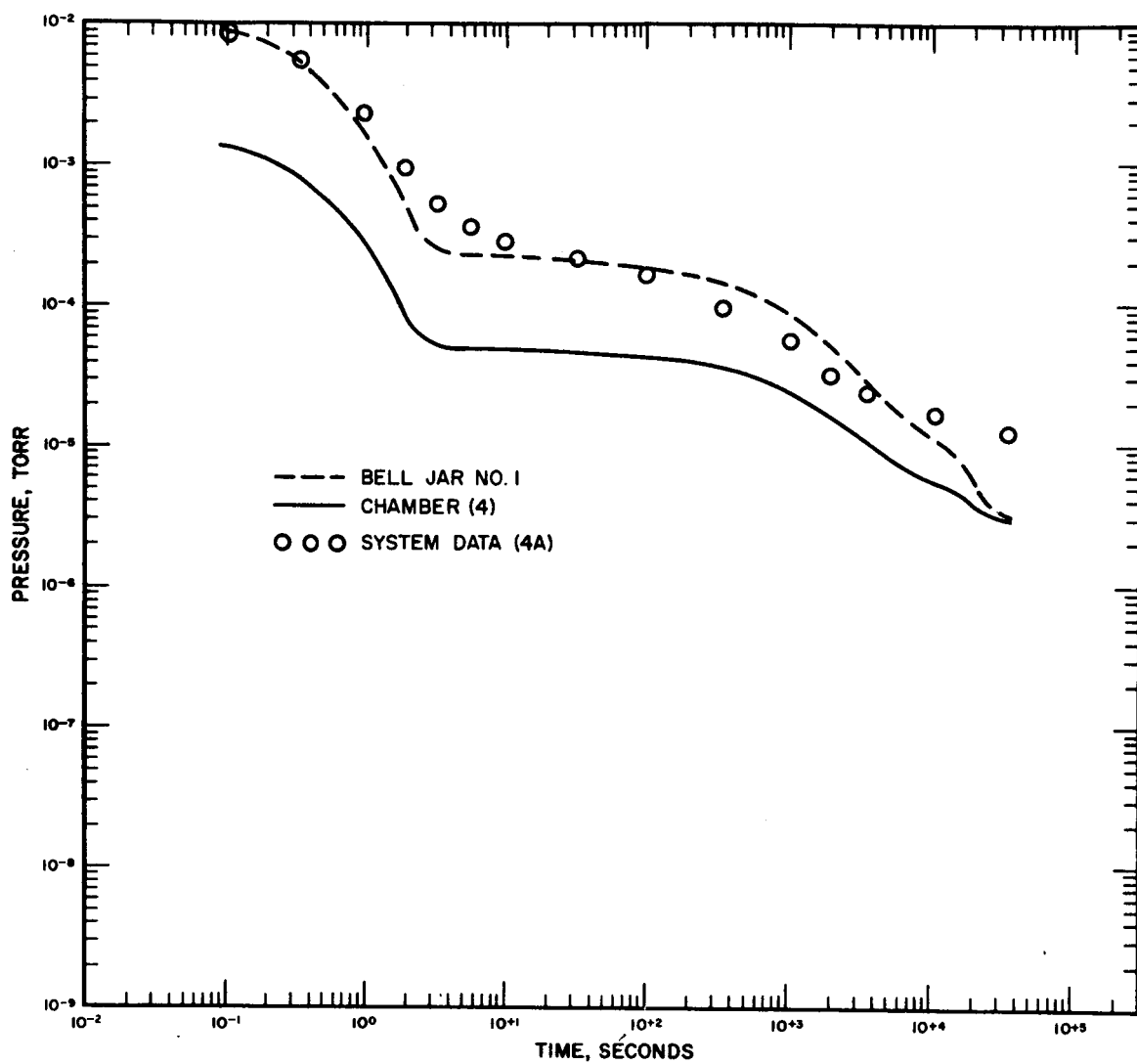
21

FIGURE 14.  SIMULATION RESULTS FOR CASE 14

December 8, 1964          APPROVAL          TM X-53175


## VACUUM SYSTEM SIMULATION AND
## MULTIPORT SYSTEM FEASIBILITY STUDY


By


C. T. Egger and J. B. Gayle


The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.


_____

W. A. RIEHL
Chief, Chemistry Branch


_____

W. R. LUCAS
Chief, Materials Division


_____

F. B. CLINE
Acting Director, Propulsion and Vehicle Engineering Laboratory

DISTRIBUTION

I-DIR               Mr. Hueter
I-SE-CH             Dr. Mrazek
I-V-DIR             Dr. Rudolph
I-V-SIVB            Mr. Godfrey
R-P&VE-DIR          Mr. Cline
R-P&VE-V            Mr. Aberg
R-P&VE-S            Mr. Kroll
R-P&VE-P            Mr. Paul
R-P&VE-VS           Mr. Schulze
R-P&VE-M            Dr. Lucas    (5)
R-P&VE-M            Mr. Zoller
R-P&VE-ME           Mr. Kingsbury
R-P&VE-MM           Mr. Cataldo
R-P&VE-MN           Mr. Shannon
R-P&VE-MNP          Mr. Curry
R-P&VE-MC           Mr. Riehl   (50)
R-SA                Dr. Kuettner
R-ASTR-DIR          Dr. Haeussermann
R-RP-DIR            Dr. Stuhlinger
R-QUAL-DIR          Mr. Grau
R-AERO-S            Mr. Ballance
R-TEST-DIR          Mr. Heimburg
CC-P                Mr. Wofford
MS-H                Mr. Akens
MS-IP               Mr. Remer
MS-IPL              Miss Robertson   (8)
MS-T                Mr. Wiggins
R-P&VE-RT           Mr. Hofues


Scientific and Technical Information Facility   (25)
Attn:  NASA Representative (S-AK/RKT)
P. O. Box 5700
Bethesda, Maryland 20014

24

DISTRIBUTION (Concluded)


Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91103
Attn:  Dr. L. Jaffe

National Aeronautics & Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135


Mr. Bernard Achhammer, RRM
National Aeronautics & Space Administration
Washington, D. C. 20546


National Aeronautics & Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771
Attn:  Dr. Frankel

National Aeronautics & Space Administration
Ames Research Center
Moffett Field, California 94035
Attn:  Mr. Charles A. Hermach

National Aeronautics & Space Administration
Langley Research Center
Langley Field, Virginia  23365
Attn:  Dr. George F. Pezdirtz